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Propulsion and Auxiliary Systems Department
Research and Development Report

On-Line Wear Particle Monitoring Based on Ultrasonic Detection and Discrimination

by
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The David Taylor Research Center and the U.S. Naval Academy, Electrical Engineering Department developed an ultrasonic technique for the nondestructive evaluation of shipboard machinery conditions. The ultrasonic wear particle sensor (UWPS) quantitatively measures the amount and size of wear-generated debris in the machinery lubricating oil by employing wide-band, ultrasonic pulse echo techniques. In addition to its present capability to detect, count, and size wear debris over a broad range of sizes, several methods of electronically discriminating contaminant particles from air bubbles have been demonstrated experimentally.

The UWPS presently exists as a microprocessor-controlled laboratory instrument. An earlier version of the UWPS successfully detected and counted wear particulate generated by oil-lubricated, rolling element bearings in serveral bearing failure tests. The instrument ~~used in these tests~~ did not discriminate air bubbles from wear debris but was

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This report discusses the theory of operation of the UWPS, methods used for determining the size of individual scatterers, and the various methods of discriminating wear debris from entrained air. Test data are presented, and possible applications are discussed. It is felt ~~that~~ this instrument will be a powerful tool for nondestructively determining the wear condition of hydraulic and lubricating oil machinery.

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CONTENTS

FIGURES

ABBREVIATIONS

ACFTD	Air Cleaner Fine Test Dust
ADC	Analog-to-digital converter
DTNSRDC	David Taylor Naval Ship Research and Development Center
DTRC	David Taylor Research Center
PHA	Pulse height analysis processor
RF	Radio frequency
UWPS	Ultrasonic wear particle sensor

ABSTRACT

The David Taylor Research Center and the U.S. Naval Academy, Electrical Engineering Department developed an ultrasonic technique for the nondestructive evaluation of shipboard machinery conditions. The ultrasonic wear particle sensor (UWPS) quantitatively measures the amount and size of wear-generated debris in the machinery lubricating oil by employing wide-band, ultrasonic pulse echo techniques. In addition to its present capability to detect, count, and size wear debris over a broad range of sizes, several methods of electronically discriminating contaminant particles from air bubbles have been demonstrated experimentally.

The UWPS presently exists as a microprocessor-controlled laboratory instrument. An earlier version of the UWPS successfully detected and counted wear particulate generated by oil-lubricated rolling element bearings in several bearing failure tests. The instrument used in these tests did not discriminate air bubbles from wear debris but was successful in detecting abnormal bearing wear. Three methods have been investigated which may ultimately provide the instrument with the ability to identify scatterers as either air bubbles, water droplets, or debris particulate. One method uses the intensity vs. the angle of scatter of the ultrasonic pulse to discriminate air from debris. Another method is based upon phase measurements of the reflected pulse echo. The latest method investigated measures the spectra of the individual pulse echoes and correlates the spectral features with particle composition.

This report discusses the theory of operation of the UWPS, methods used for determining the size of individual scatterers, and the various methods of discriminating wear debris from entrained air. Test data are presented, and possible applications are discussed. It is felt that this instrument will be a powerful tool for nondestructively determining the wear condition of hydraulic and lubricating oil machinery.

ADMINISTRATIVE INFORMATION

This work was performed under program element 63513N (from FY 84 through FY 87), task area S0382SL003, and work unit number 87-1-2753-120. This report summarizes the work performed from February 1984 to October 1987, as well as the present status of the project.

INTRODUCTION

Information obtained from the analysis of the micron-sized wear debris generated by bearings, gears, and other moving machine parts has proven to be useful for detecting and predicting machinery failures. An ideal wear particle monitor and analyzing instrument would provide wear debris count, size distribution, rate of generation, and identification or discrimination of wear debris and other entrained contaminants. While many available particle monitoring instruments provide particle counting and sizing capabilities, no single method has been able to provide particle characterization information while on-line.[1] To date, particle discrimination requires the sampling of lubricating or hydraulic fluid for off-line testing. This subjects the testing to possible operator error, and the information obtained is generally not timely.[2]

A relatively new technique which has the potential for solving some of these problems uses pulsed ultrasound for wear particle detection.[3,4] The instrument monitors the full lubricant flow within a pipe by using a focused acoustic transducer mounted through the pipe wall. The transducer both radiates a large amplitude radio frequency (RF) pulse and "listens" for pulse echoes returned from particles in the flowing oil stream. Particle size and count distributions are built from large accumulations of pulse echo data. Although commercially available, the use of ultrasonics for wear debris monitoring has not been widespread, primarily because of the limited success in distinguishing wear debris from the entrained air and water frequently found in machinery lubricating oil systems. The ultrasonic wear particle sensor (UWPS) is capable of detecting, counting, and sizing wear debris over a broad range and can discriminate particulate, air, and water. Theory, calculations, and supporting test data are presented which demonstrate the principles of operation of the UWPS and the three discrimination techniques developed.

SYSTEM DESCRIPTION

The basic UWPS is shown in Fig. 1. The RF pulser provides a sequence of large amplitude electrical pulses, called the "main bang," which excite the transducer at its resonant frequency. The transducer couples the "main bang" pulse to the oil as acoustic energy. After the "main bang" subsides, particles passing through the acoustic field reflect or echo the "main bang." Pulse echoes are detected and reconverted to RF energy by the transducer. The receiver amplifies the microvolt level pulse echoes, and the peak detector measures the amplitude of only those pulse echoes occurring in the focal region of the acoustic field by means of an electronic time gate. This is more clearly represented by the electrical signal trace shown in Fig. 1, where the "main bang," a particle echo occurring in the gated window, and the rear pipe wall reflection are shown.

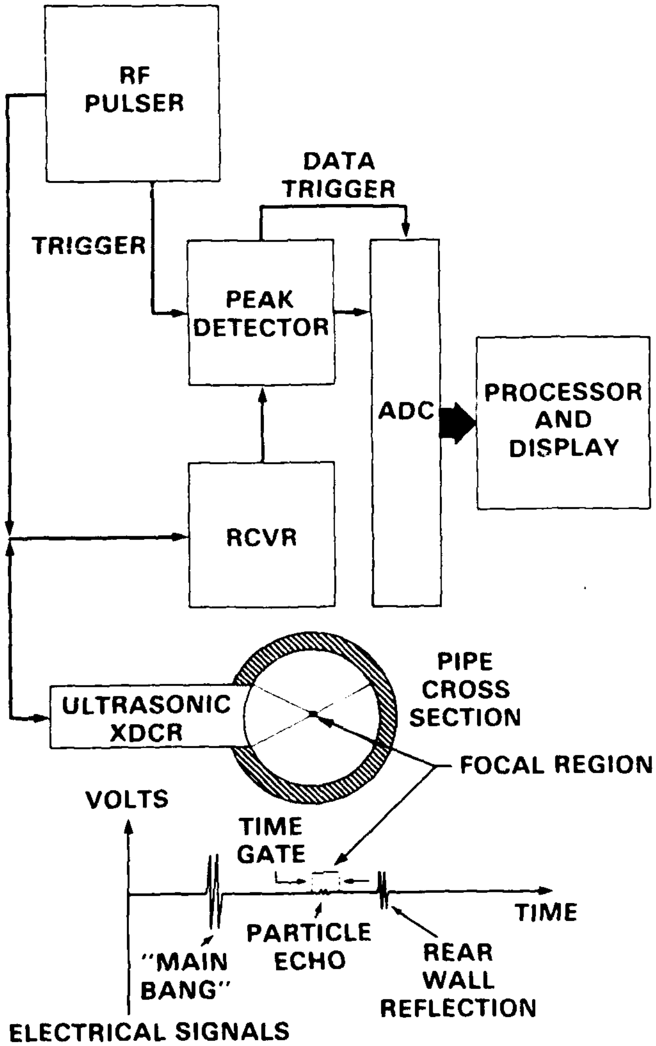

Fig. 1. UWPS block diagram with electrical trace showing "main bang," gated-window, particle echo, and rear pipe wall reflection.

The largest echo amplitude measured for each repetition of the "main bang" is digitized by the analog-to-digital converter (ADC), which increments an address in a buffer corresponding to the echo amplitude. When the desired number of pulses is collected, the ADC ceases digitizing pulse amplitudes and alerts the pulse height analysis (PHA) processor. The PHA processor receives the data as an array. The order of the array represents pulse amplitude, and the array values represent the number of occurrences of pulses of that amplitude. The information can then be displayed, processed further, or stored for future reference by the processor.

PARTICLE DETECTION AND COUNTING

Particles are detected and counted when a particle present in the focal region produces a pulse echo with an amplitude greater than the noise threshold of the system. Pulse echoes below the noise threshold, i.e., particles smaller than the minimum detectable size, are counted as zero amplitude echoes. For a 95% statistical confidence in the measurement, 32,000 pulse echoes must be collected with a signal (pulse echo) to noise ratio of greater than 7 dB.[5] In order to satisfy this, the UWPS is generally set to collect 60,000 data points in 1-minute intervals at a "main bang" repetition rate of 1 kHz.

The number of counted particles can be related to concentration based on the measurement volume of the acoustic focal region. Figure 2 shows the acoustic field pressure along the *Z* axis, away from the transducer face, and a cross section of the field at the focus along an *r* axis perpendicular to *Z*. This measurement volume is modeled as a cylinder of volume $V=2\pi\ r_1 ct$, where c is the speed of sound in oil, t is one-half the duration of the gated window (taking into account the overall (to and from) time of the acoustic pulse) and r_1 is the radius of the 6 dB beam width at the focus. The maximum concentration of particles that can be reliably measured is one particle per sample volume. When the concentration exceeds this, co-occurrence of particles at the focus takes place and additional particles in the system do not increase the measured count linearly.

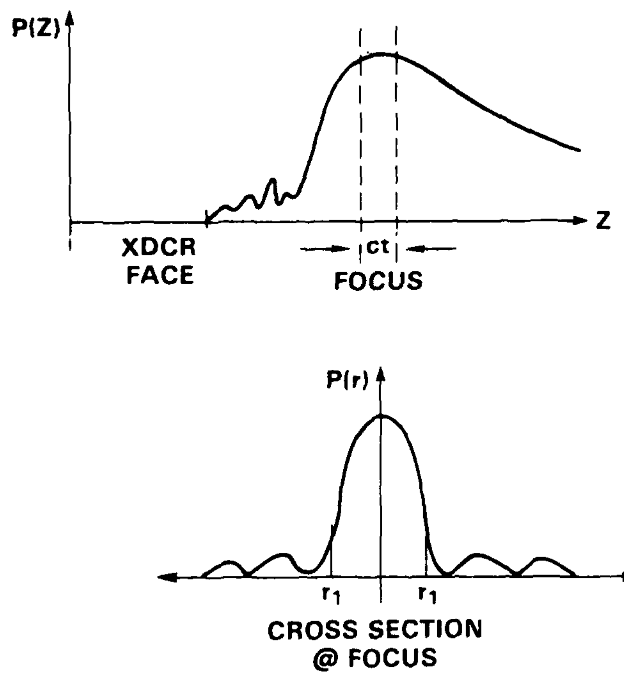

Fig. 2. Idealized plot of the ultrasonic field intensity from a focused transducer.

PARTICLE SIZING

The remaining task is to correlate physical particle size with pulse echo amplitude. Each spherical Rayleigh scatterer generates a reflected signal with voltage amplitude:

$$V \propto D^3 * P_0(Z), \text{ when } \lambda >> D,$$

where D is the diameter of the particle, $P_0(Z)$ is the intensity of the acoustic field seen by the particle, and λ is the wavelength of the acoustic beam. Using a focused transducer creates a region of high intensity acoustic pressure, which is useful for the detection of small particles but creates sizing problems because of the spatial variation of the acoustic field intensity. As shown in Fig. 2, the acoustic field intensity is nearly uniform at the focus along the Z axis but decays as a first order Bessel function along r. Since information about the particle's exact location along r is unknown, the magnitude of $P_0(Z)$, as seen by the particle, cannot be determined. Statistical methods exist, however, to reliably extract particle size from accumulated echo amplitudes.[4,5,6] One developed method uses multiple linear regression models built from large accumulations of controlled laboratory data. The software for the linear regression models can be programmed into the PHA processor and can convert pulse amplitudes into discrete particle sizes, ranging from 15 microns to 105 microns. Although not fully tested, this method has proven to be reliable with error rates within those specified for industrial particle counters.[7]

PERFORMANCE DATA

Laboratory testing of the UWPS was conducted on an oil circulating loop using measured amounts of calibrated glass beads and Air Cleaner Fine Test Dust (ACFTD). Testing demonstrated that using a 5-MHz transducer with a 0.64-cm (0.25-in.) active element and a 1.52-cm (0.6-in.) focal length in oil, the unit is capable of detecting and counting particulate ranging from approximately 3 microns up to 2,000 microns in diameter in concentrations ranging from 0.01 ppm to 12.8 ppm. These ranges represent the limits of the test conditions.

Additional testing of the UWPS was performed on five bearing failure tests.[8] These tests were conducted on a machine that permitted a set of four single-row, oil-lubricated ball bearings to be run to failure on an accelerated basis. In addition to the UWPS, other monitoring instrumentation collected data during the tests. The UWPS detected and counted wear debris in the presence of entrained air; particle count data collected by the UWPS correlated well with bearing wear events, e.g., spalling. Figure 3 shows particle count data of a single size collected by the UWPS plotted against accelerometer data over the life of the fifth bearing test. The graph

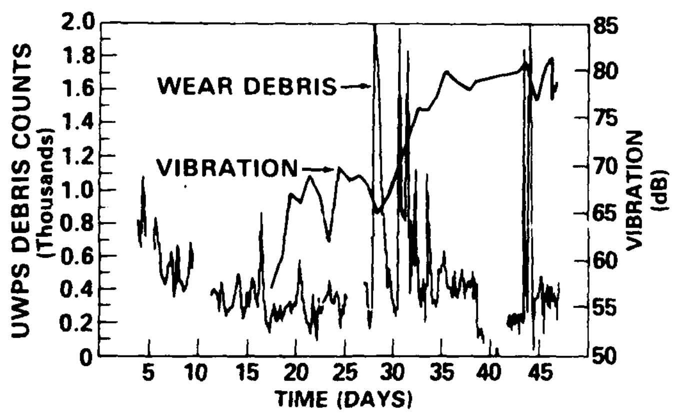

Fig. 3. UWPS data and accelerometer data during a bearing failure test.

shows that on several occasions during the test the UWPS recorded large amounts of wear debris being generated by the bearings. The vibration intensity measured with the accelerometers increased significantly on the 16th day and again on the 27th day, which corresponded to periods when the UWPS recorded a large amount of debris generation. The frequency of the vibration data plotted corresponded to that of an outer race bearing defect. At the test's conclusion, it was found that one of the bearings had failed, in part, due to an outer race spall. Although the particle data collected during these tests was not quantified with physical particle size, the tests demonstrated the feasibility of the UWPS.

The bearing tests established the need to distinguish the wear debris from entrained air and water in the lubricating oil, if accurate particle counts were to be acquired. To aid this process a hydrocyclone was installed in the oil line on later tests to concentrate the debris and remove some of the 2% entrained air. The resulting levels of entrained air were still comparable with the levels of wear debris, demonstrating the need for a method for discriminating among echoes from air bubbles, water droplets, and wear debris.

AIR, WATER, AND PARTICLE ECHO DISCRIMINATION

Three methods were identified for discriminating among the acoustic echoes originating from air bubbles, water droplets and solid particles. They were off-angle scattering, phase shift (measured in the time domain), and spectral analysis of the echoes. Each method has been confirmed experimentally and is discussed.

OFF-ANGLE SCATTERING

A means of separating particle echoes from air echoes is achieved by taking advantage of the fact that air bubbles scatter an ultrasonic pulse uniformly in all directions, while hard particles primarily backscatter the pulse. Classical acoustical physics reveal that the variation of the pressure amplitude scattered from a spherical particle (smaller than the source wavelength) depends, in part, upon the ratios of the density and compressibility of the particle to the fluid. All other variables can be assumed to be constant when the magnitude of the reflected pulse echo at some specified angle off- axis is compared to the backscattered signal in real time.[9] An equation was derived for this model and the magnitude of the scattered signal calculated vs. the angle of scatter. This was performed for air, water, glass, and steel in lubricating oil; the result is plotted in Fig. 4. In the graph, 0° is forward scatter (away from the source transducer), and 180° is direct backscatter. The plot reveals that the reflected echo from a steel particle at a forward angle of 40°

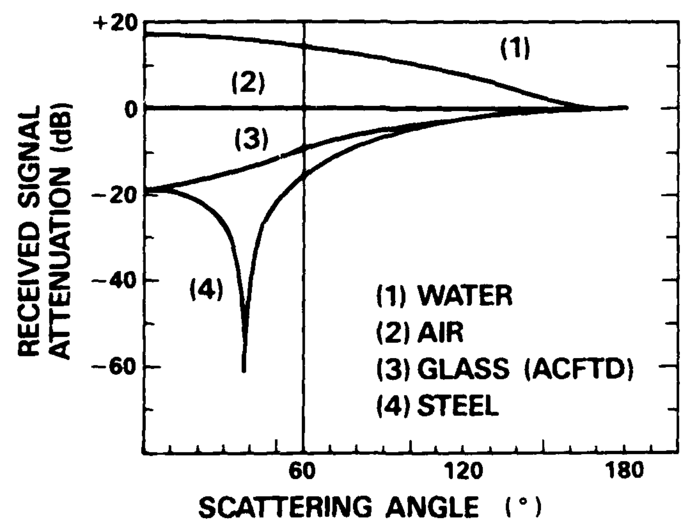

Fig. 4. Reflected signal vs. angle of scatter for air, water, glass, and steel in oil.

is more than 60 dB lower than the backscattered pulse. By placing an additional transducer opposite the pulsing transducer at this angle off-axis and simultaneously measuring echo amplitude received by each transducer, discrimination among air bubbles, water, and particulate is possible.

Implementation of the off-angle scattering version of the UWPS uses three transducers equally spaced at 120° angles around the pipe. The advantages of a 60° forward angle vice the 40° angle consist of the following:

1. Reduced transducer crosstalk;
2. Interchangeability of the transducers in terms of which transducer is to be used as the pulsing transducer; and
3. Elimination of "blind spots," which occur when fewer transducers are used. "Blind spots" arise from the narrow, Bessel shape of the acoustic field.

This UWPS package, shown in Fig. 5, requires two more transducers, receivers, and peak detectors than the basic model. The transducers, receivers, and peak detectors are all matched to exhibit the same gain, and the gated windows of the peak detectors are each set to overlap each other spatially. With this

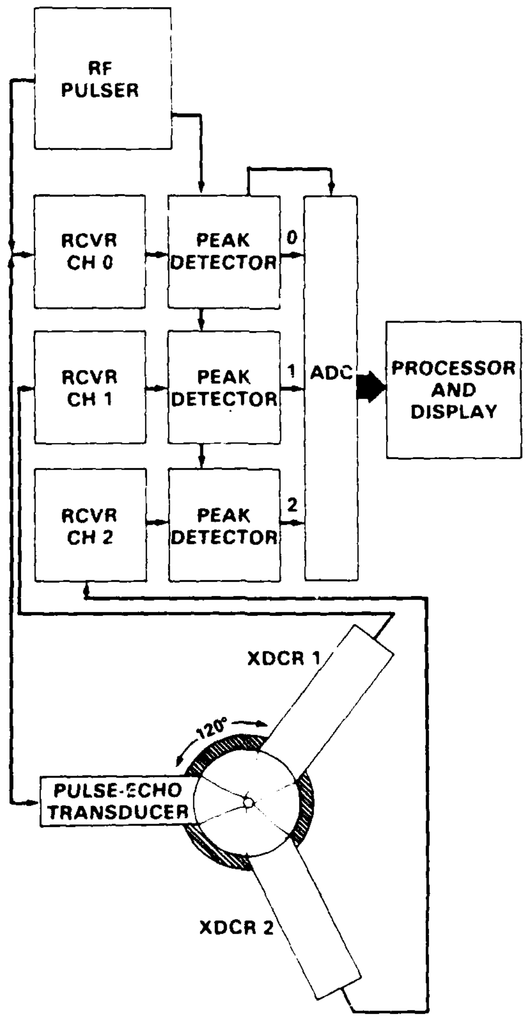

Fig. 5. Block diagram of the off-angle scattering version of the UWPS.

setup the peak detectors simultaneously transmit the captured peak level to their assigned ADC channel. The trigger allows the conversion of the data in a sequential fashion, starting with channel 0 (the backscatter transducer). The software then compares the digitized value of the backscattered echo (at channel 0) with those of the forward scatter channels, 1 and 2. Based on this comparison, the echo is classified as either air, water, or particle, and the appropriate array or bin is incremented.

This version of the UWPS was tested on the oil recirculating loop with entrained air, glass beads, and steel particles. Experimental collected data confirmed that particle discrimination was reliable for concentrations of air bubbles, up to the point of constant co-occurrence of bubbles and particles in the focal region. The performance limits of this version of the UWPS remain to be fully quantified.

PHASE SHIFT

Echo classification for discriminating between air and particles can be achieved by sorting detected echoes according to their acoustic hardness. One bin would contain echoes from scatterers with acoustic impedance less than that of the surrounding fluid. These are referred to as acoustically soft particles. The other bin would contain echoes from scatterers that were acoustically hard, such as metal wear debris. Relative acoustic impedance is defined as the acoustic impedance of the scatterer divided by that of the fluid. Metal particles are acoustically hard, possessing a relative acoustic impedance ranging from 10 to 100. Air bubbles, however, are acoustically soft with a relative impedance near zero.

Virtually all particle discrimination schemes utilizing backscattered acoustic energy employ the principle outlined in the previous paragraph, but they may use different signal features, pattern vectors, or analysis domains. In practice, even a binary classification scheme is very useful because entrapped air bubbles in the fluid lead to large error in wear particle counting. For all of the methods, pulse height analysis is required for each class or bin to obtain particle size distribution functions.

The phase of a pulse reflected from a scatterer in a liquid depends upon the relative acoustic impedance of the particle to the liquid. The phase of an echo reflected from an acoustically soft particle such as air is inverted 180° relative to the echo from an acoustically hard particle such as metal.[9] Measurements of acoustic echoes from tungsten particles and air bubbles confirm this phase change, as illustrated in Figs. 6 and 7. The initial half cycle for the air echo is positive; for the tungsten particle it is negative. Theoretically, the opposite is true; however, the electronics inverted the pulse echo polarity. From Figs. 6 and 7, it is also apparent that the air echo displays a single, large negative peak, while the tungsten has one large positive peak.

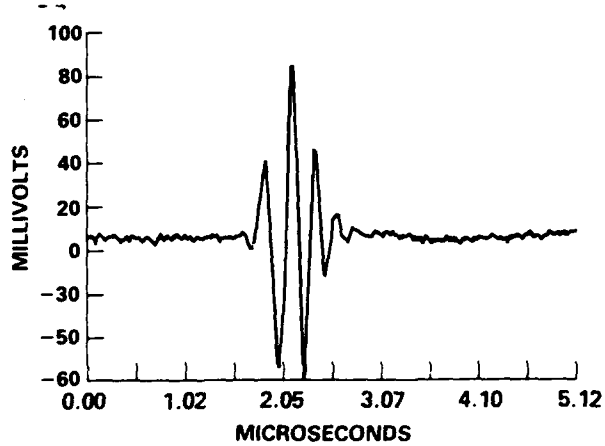

Fig. 6. Tungsten particle echo.

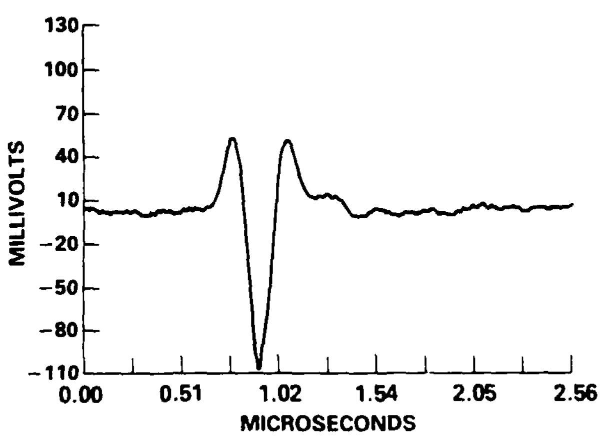

Fig. 7. Air bubble echo.

This discrimination method could be implemented, as shown in Fig. 8. In this case, the discriminator box shown in Fig. 8 would perform a fast digitization of the received pulse echoes and by means of a simple algorithm, differentiate echoes based upon their phase. The decision would then be sent to the pulse height processor's ADC board so that received echoes could be sorted into their respective bins.

There are problems with using phase to discriminate particles from air. When the scatterer is not in the center of the beam, the frequency content of the acoustic field is different and, sometimes, the time signal of the echo from an air bubble looks very similar to that of a metal particle. Data from the UWPS system show that most of the time the time signal is sufficiently different in phase (and frequency) content so that a reasonably accurate discrimination could be made between air and metal particles, provided the echoes do not overlap in time.

SPECTRAL ANALYSIS

The scattering of acoustic waves by solid cylinders and spheres is well documented, with Faran[10] and Hickling[11] being the early investigators. More recently, resonance scattering theory was developed by Flax, Gaunaurd, and Uberall[12] and was applied to cylindrical and spherical targets.[13, 14, 15] However, most of the early scattering experiments were performed on large targets at low frequencies. The availability of high frequency, wide bandwidth ultrasonic transducers has made another means of wear particle characterization feasible. Recently, the spectra of ultrasonic pulse echoes from small (100-micron to 2,000-micron) solid spheres and air bubbles in fluids were measured in the 1 MHz to 14 MHz frequency range.[16] This use of spectral analysis for particle discrimination has been made practical by using a novel inverse filter correction

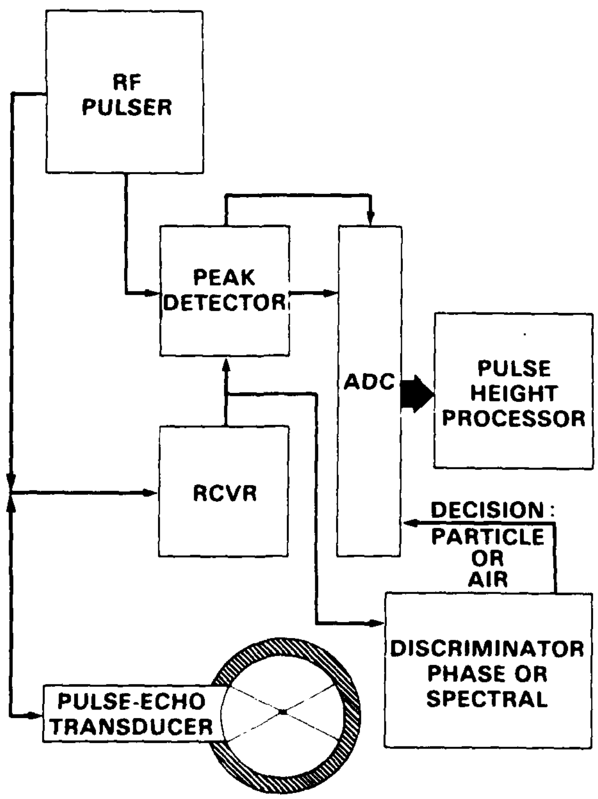

Fig. 8. Block diagram for both the phase and spectral analysis versions of the UWPS.

to remove the spectral coloring of the measurement system such as the transducer, pulser, amplifier, and fluid.

Inverse filtered echo spectra for 300-micron spherical copper and air targets are shown in Figs. 9 and 10, respectively. The spectral function obtained from the copper target is in good agreement with the shapes predicted by the resonance scattering theory. The spectral line separation of approximately $ka = 4$ (ka represents the wavenumber multiplied by the scatterer radius) displayed in Fig. 9 is also in accordance with the theory. For the air bubbles, the same theory predicts a spectral line separation of approximately $ka = 0.05$, but because of the narrow time domain data window used in this measurement, the closely spaced lines cannot be resolved and only an integrated continuum is obtained.

These spectral differences are utilized in the signal processing algorithms to discriminate between the "finger-like" spectral features of the solid particles from the relatively flat and featureless spectral shape of the air bubbles. This method has been implemented in the laboratory and is shown in Fig. 8. The discriminator block in Fig. 8 includes a unique 42-MHz, 8-bit ADC, which digitizes the reflected pulse echoes. Although the individual echoes are presently analyzed off-line, a series of matched digital filters or some other digital algorithm could be implemented to discriminate particles from air or water.

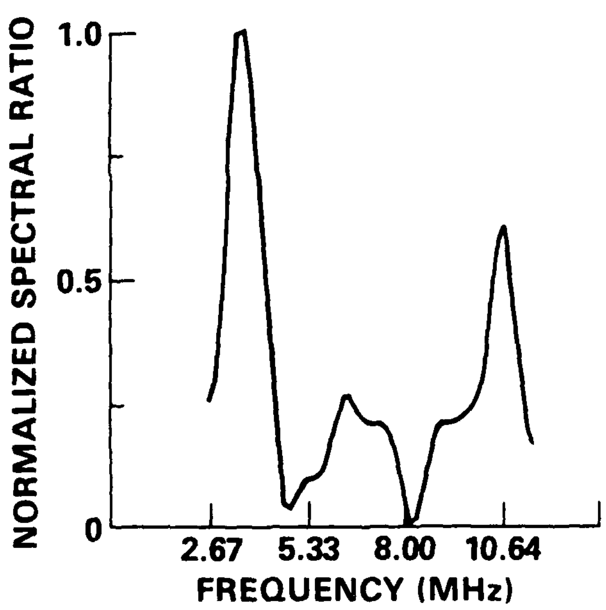

Fig. 9. Spectral shaping of a 300-micron copper sphere.

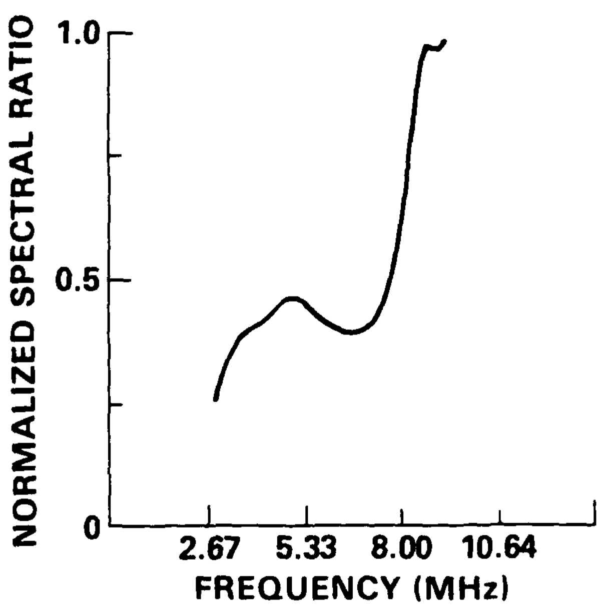

Fig. 10. Spectral shaping of a 300-micron air bubble.

SUMMARY

The UWPS has proven to be a feasible means of detecting, counting, and sizing wear debris in lubricating oil systems. The three methods of particle, air, and water discrimination discussed in this report have both advantages and disadvantages. To date, the off-angle scattering scheme has been built and tested as an on-line means for separating debris counts from air and water. Further quantification of the full performance of this instrument and refinements in its software algorithm are anticipated. Despite being hardware-intensive and having problems associated with critically aligning three transducers, this method is essentially fully developed.

The spectral analysis and phase angle methods of discrimination hold the most promise for the implementation of a relatively inexpensive single transducer UWPS capable of discriminating wear debris from entrained contaminants. These methods require further design and testing.

CONCLUSION

The intended use of the UWPS is for the monitoring of wear debris in critical shipboard machinery and engine lubricating oil and hydraulic systems, but it could include other similar industrial applications. The benefits provided by the UWPS may include faster troubleshooting and detection of impending machinery failures, thus extending overhaul periods and reducing secondary failures. Given its unique features, the UWPS may prove to be a useful tool for the nondestructive monitoring and trending of shipboard machinery wear.

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